

Integration of Safety and the *Highway Capacity Manual*

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1. ABSTRACT

Users of the *Highway Capacity Manual*, which is the primary tool used for analysis and design of highway facilities in the U.S., make recommendations and decisions that affect highway safety. Yet, their decisions are made based primarily on operational measures using the level of service concept. This paper examines the major issues involved in integrating safety into the Manual, characterizes the ideal traits of an assessment tool based upon that discussion and presents a prototype methodology for chapter 9—signalized intersections. Fuzzy sets are proposed as one tool that has the characteristics described. An example using Fuzzy sets illustrates some of the main tasks required for implementation and, at a conceptual level, describes the various models used.

2. INTRODUCTION

Users of the *Highway Capacity Manual* (TRB, 1997), which is the primary tool used for analysis and design of highway facilities in the U.S., make recommendations and decisions that affect highway safety. Yet, their decisions are made based primarily on operational measures using the level of service concept. These users, who typically have no specialized training in the critical area of highway safety, must be provided guidance in safety matters when applying the Manual if safety is to be effectively included in the decisionmaking process (Hauer, 1999). This paper describes work, on-going at the University of Missouri-Rolla (UMR), whose primary purpose is to examine ways in which safety can be integrated into the Manual and to develop a prototype methodology for Chapter Nine, signalized intersections, and to make preliminary recommendations for further research in the area. The paper's focus is on issues associated with the development of a comprehensive safety-based *Highway Capacity Manual*.

3. BACKGROUND AND RATIONALE

The *Highway Capacity Manual* established the concept of "Level of Service" for measuring the quality of the driver's experience on a highway facility. It uses level-of-service, the commonly accepted measure of effectiveness for highway analyses, to translate the numerical results of traffic operations analyses into letter grades more readily understandable by the general public. The assignment of letter grades for level of service has been enormously successful, having been incorporated into numerous state and local legal codes for measuring the impacts of new development and monitoring congestion.

Current level-of-service evaluation criteria do not include safety measures. The HCM (*Highway Capacity Manual*) is a collection of facts and procedures that allows the analyst to determine relationships among physical characteristics, operational characteristics and level of service. At present, safety is not included in the Manual. Available information on the safety

effects of operational design decisions is not readily usable to evaluate and compare design alternatives. There currently exist no tools to help the traffic practitioner determine the likely impact on safety of operational changes such as installing a traffic signal or changing lane use, or providing bus access at a signalized intersection. Lacking convenient evaluation tools limits designers' ability to detect potential safety problems in design, select safety cost-effective design parameters, compare the safety of design alternatives, or to optimize the safety of particular designs. As a result, differences in safety performance may not be given due consideration when deciding among design alternatives.

The original definition of level of service, as it pertains to highways, was given in the 1965 *Highway Capacity Manual* (HRB, 1965) as follows:

Level of service is a qualitative measure of the effect of a number of factors, which include speed and travel time, traffic interruptions, freedom to maneuver, safety, driving comfort and convenience, and operating costs.

Note that the definition explicitly names safety as one of the qualitative measures of LOS. Delay has subsequently been used as the sole LOS measure at signalized intersections. It can, arguably, be used as a surrogate for qualitative measures such as convenience and operating costs but not for safety.

The UMR Study has been examining what would need to be done if safety were to be added to the HCM. There exist several possible scenarios—thus, the objective of the research to examine these scenarios and to make preliminary recommendations for further research in the area.

4. DISCUSSION OF ISSUES

4.1 Use of a Safety LOS

Current LOS criteria for signalized intersections, as they are presented in the HCM, were established based upon the acceptability of various delays to drivers (TRB, 1985), the assumption being that delay reflects drivers' subjective perceptions of freedom, convenience and comfort. Hauer (1999) uses this to argue against including a "safety-related" LOS measure:

In the LOS now in use, perception is the central notion and objective measurements are used to reflect it. Because the two are likely to go hand in hand the substitution of one by the other may not cause problems. In safety one may not assume that what makes road users feel safer will cause fewer or less severe accidents. Therefore, one will not be able to claim that 'measures of effectiveness' such as accident frequency or severity are legitimate measures of what people think of as LOS.

Hauer's premise is that we should design facilities based upon users' perceptions of utility—and this is indeed what is attempted in the LOS now in use, as he points out. User perception, however, is often not the criterion used for assessing "system" needs. Indeed,

in more complex situations than a single intersection (e.g., a major corridor study), there are multiple factions of users, or stakeholders, all with competing needs and desires. Many of the measures of effectiveness used are contrary to an individual user's perception of the service quality he or she experiences—similar to Hauer's point regarding safety measures. Thus, the fact that safety does not directly relate to user perceptions of service quality should not be used to argue against its use as a LOS indicator.

4.2 Difficulties with Current LOS Measures at Signalized Intersections

As stated above, the HCM uses distinct delay values as boundaries for the various levels of service. There exists an inherent weakness in this approach given the qualitative nature of LOS. The use of distinct boundaries of a sole measure limits the accuracy with which an intersection may be characterized. It does not provide access to the rich vocabulary of linguistic uncertainties associated with LOS. In addition, there exist difficulties in setting distinct boundaries for qualitative measures. For example, the difference between 5 seconds of delay and 5.5 seconds is surely not a full level of service, at least not in terms of user perception. Furthermore, delay is not the only measure important to the users' perception of service quality (TRB, 1985). Use of delay as the sole measure may lead to misleading conclusions. For example, a LOS F determination does not automatically imply that the intersection is overloaded, nor does a LOS A through E automatically imply that there is unused capacity available.

4.3 Current Safety Models

If safety were added to the current HCM procedures, safety-related definitions, concepts and descriptions of relevant observed values would need to be added. Procedures for calculating safety-related measures of effectiveness would also need to be added, which leads one to question whether the state of safety knowledge is adequate for this.

There has been a wealth of research into accident prediction modeling and the place of safety in assessing operational performance of highways. Substantial research, for example, has been conducted on the safety effects of various freeway interchange elements, as reported in a summary of research on interchange safety prepared in the early 1990s by Twomey, Heckman, and Hayward (1992). Earlier sources include an annotated bibliography prepared in the early 1980s by Harwood et al. (1982 and 1983) and a summary of research findings prepared by Oppenlander and Dawson in 1970. Cirillo et al. (1969) describe six multiple regression models to predict accident frequencies for entire interchange areas and 13 models of specific interchange components, including ramps and speed-change lanes. Accident severity distributions were also examined. Traffic volumes were found to be a key variable in predicting interchange accident experience. Geometric features of ramps considered in accident modeling included ramp type (on-ramp vs. off-ramp), ramp length, speed-change lane length, presence of curvature, maximum curvature on ramp, central angle of first curve on ramp, ramp grade, right and left shoulder widths, minimum stopping sight distance, and difference between ramp and speed-change lane design speeds.

Several U.S. and European studies described in Lamm et al. (1999) have examined the relationships of grade, volume, and sight distance with accident experience on a variety of

other facility types as well. Hauer et al. (1988) developed a series of 15 models per approach (one model for each major accident pattern) for signalized four-approach intersections from data on 143 intersections in Toronto, Ontario. The models are logical, fit their data well, and are widely accepted in the profession. Zegeer et al. (1991) developed accident prediction models for curves on two-lane roads for the Federal Highway Administration using databases of 10,000 non-isolated curves in Washington state and over 3,000 isolated curves from several other states. More recently, Vogt and Bared (1998) built accident models for segments of two-lane rural roads and for three- and four-legged stop-controlled intersections. A model developed by Turner (1984) from over 2,000 bridges in Texas predicts accident rates at bridges on two-lane roads based on volumes and geometrics. Bonneson and McCoy (1993) applied a generalized linear modeling approach to the development of a model relating unsignalized intersection traffic demands to accident frequency. The analysis of accident data for 125 two-way stop-controlled intersections supports the theory that the distribution of accident counts can be described by the negative binomial distribution. Belanger (1994) developed multivariate models for estimating the number of accidents at four-legged signalized intersections based primarily upon traffic flow functions. Attempts were made to develop models for specific patterns of collisions and to incorporate variables other than traffic flow functions to these models. McGee (1997), as part of a NCHRP-funded project, is developing an improved accident warrant for traffic signals and models to estimate the safety impacts of installing or removing traffic signals. Finally, Persuad et al. (1998) developed a set of disaggregate safety performance models for signalized intersections which may be used for exploring the safety effects of alternate re-design options.

Substantial safety modeling has been (and is being) done with regard to geometric design as well. The Federal Highway Administration's Interactive Highway Safety Design Model (IHSDM), is a suite of CADD-compatible programs composed of safety analysis modules that highway designers can use to evaluate the safety effects of various design alternatives (Giering and Bared 1997). In a 1997 study, funded by the Federal Highway Administration, Bauer et al. developed statistical models for defining the relationship between traffic accidents and highway geometric design elements and traffic volumes for interchange ramps and speed-change lanes.

4.4 Integration of Safety into the HCM

If a safety LOS were to be introduced into the HCM a decision regarding the final form of LOS would need to be made, namely, should the operational and safety measures be considered separately, or should they be combined in some way. In any event, their differences would need to be resolved. Paraphrasing Hauer (1999): what is good for safety is not necessarily good for mobility. At signalized intersections, for example, the use of more phases increases safety but also increases delay.

Studies which have attempted to assign level of service to safety measures have made significant progress in moving toward a safety-based assessment of facilities but have several deficiencies. In 1995, Lee et al. developed safety-based level-of-service parameters for two-way stop-controlled intersections. A simulation model was used to generate case studies which were in turn used to calibrate regression models that attempted to measure the safety of two-way stop-controlled intersections based on parameters such as

intersection geometry, traffic volume, pavement condition, traffic composition, and available sight distances. Safety-related level-of-service measures were assigned arbitrarily and were kept separate from operations-based level of service. Ha and Berg (1995) used conflict opportunity models, first proposed by Council et al. (in Ha and Berg 1995), and kinetic energy calculations for the typical crash to represent “safety” at signalized intersections. They considered left turn and rear end crash types. This “total hazard” variable was used as the level of service criterion and, as with Lee’s work, were arbitrarily assigned and kept separate from operations-based level of service. Data for this study were minimal and analysis results were poor. The safety LOS measure was insensitive to changes at the intersection while the operational LOS changed.

4.5 Discussion Conclusions

4.5.1 Use of a safety LOS

Although safety does not relate directly to users’ perceptions of service quality, a safety LOS measure which indicates service quality of the “System” makes sense given the need for such a measure described earlier in the paper.

4.5.2 Difficulties with current LOS measures at signalized intersections

- The use of distinct delay values as boundaries for levels of service is problematic. The boundaries do not accurately represent level of service, especially in transition areas, and the determination of the boundaries is a very difficult task and is likely fraught with errors.
- Delay is not the sole measure of LOS. There are other variables that should be included for a full assessment of LOS.

4.5.3 Current safety models

This sampling of the work that has been done in the area of safety modeling and prediction demonstrates that a substantial body of safety knowledge exists which is sufficiently robust (experience spanning more than 30 years) for inclusion in the HCM.

4.5.4 Integration of safety into the HCM

Efforts toward integrating safety into the HCM have been made but are few and flawed. The studies described:

- Include crash frequency and severity measures in their measures of safety but do not base models on real data.
- Provide some limited guidance on variables to include in a safety measure but provide none on mapping the measure to level of service.
- Make no attempt to (nor do they provide guidance for) combine the, sometimes conflicting, safety and operational LOS measures.
- Use the existing LOS delay boundaries and arbitrarily create new boundaries for the safety LOS measure.

5. A PROPOSED METHODOLOGY

Given these conclusions, the ideal tool for assessing level of service would be one which:

- Provides a measure of safety based upon characteristics of the site;
- Allows qualitative assessments of a variety of measures, such as safety, delay, and others, using quantitative information;
- Provides a combining mechanism to allow the integration of safety and operational levels of service;
- Avoids the use of artificial distinct LOS boundaries;
- Provides a weighting mechanism which could be specified qualitatively.

5.1 Fuzzy Sets

One tool that displays these traits is fuzzy sets. Fuzzy sets may be used to represent vague and imprecise concepts, such as intersection LOS. Expressing inexact concepts such as large or safe or old in fuzzy logic is straightforward. Fuzzy sets use membership values, indicated by values from zero to one, with 0 representing no membership and 1 representing complete membership in a set. For example, the intersection of Main and Minor is safe. Perhaps a value for a hazard index is 7 (out of a possible 10), a truth value may be assigned to represent that intersection's membership in the set of safe intersections, given its hazard index value. The truth value must derive from experiential knowledge. Perhaps in this case, Main and Minor would have a 0.8 membership value assigned. This would indicate that Main and Minor's degree of membership in the set of safe intersections is 0.8. Fuzzy logic also allows for imprecise hedges to be made. For example, there is a way to quantify the statement "Main and Minor is very safe" if the intersection's membership value is known.

Fuzzy sets consist of sets of items with their corresponding membership values. For example, consider the definitions of small, medium and large as sets of items where the sets consist of the names of items and their memberships. Medium may be defined as follows:

$$\text{Medium} = [0|0.0, 1|1.0, 2|0.3, 3|0.1, 4|0.0]$$

In this particular "Universe" (from which the set is drawn), 2's degree of membership in the set of medium-sized objects is 0.3.

The following example is provided here strictly for the purpose of illustrating the application of Fuzzy Sets to LOS assessment. Ndoh and Ashford (1994) proposes a six step process for evaluating the level of service of processes at an airport using fuzzy sets. The steps apply equally well to a signalized intersection.

1. Identify and classify the service system as a decision tree. Figure 1 depicts a possible arrangement for a signalized intersection.

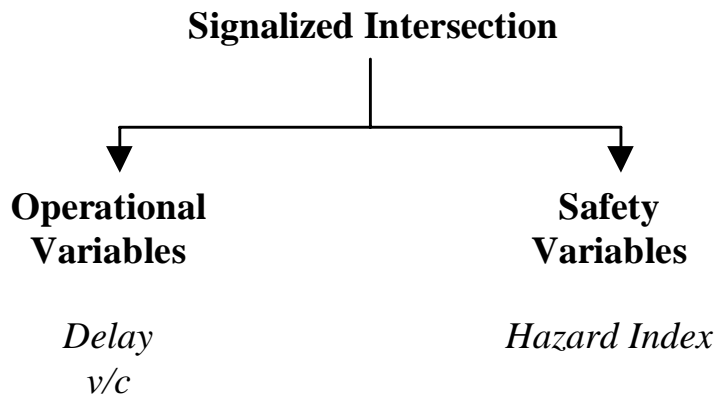


FIGURE 1 Intersection Service System.

2. Define the natural language subset for each variable appropriate for defining level of service for each component of the system. Using natural language, perhaps A could be very good, B good, C average, D fair, E poor, and F failure. Thus, since LOS A can be eliminated since it is a “hedge” that can be accommodated separately, there would be five levels of service. This could then be used in terms of delay, hazard index (as the safety measure), and any other variables desired. The individual variables could then be weighted using another set of fuzzy values representing relative importance. For example, each variable would be of low, medium or high importance.
3. Establish membership functions for each of the variables defined above. This would require the acquisition of knowledge. For this example, the LOS definitions, for operational level of service, are taken directly from the *Highway Capacity Manual*, resulting in the functions shown in Figure 2. There are 15 delay categories consisting of 0 to 5 seconds, 5 to 10 seconds, up to 70 to 75 seconds.

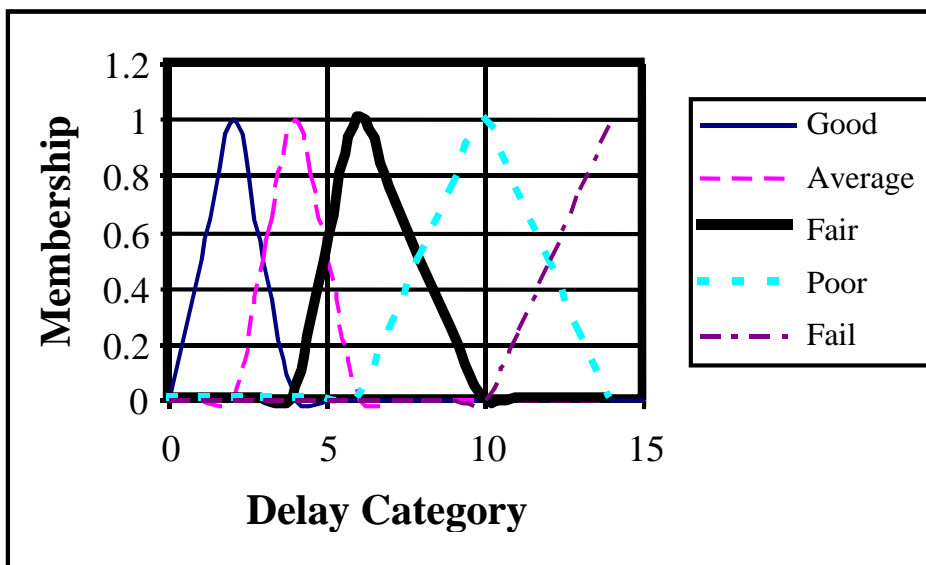


FIGURE 2 Sample Membership Functions.

Thus, the following LOS sets may be established for operational LOS:

Good = [0|0.0, 1|0.5, 2|1.0, 3|0.5, 4|0.0, 5|0.0 ... 15|0.0]

Average = [0|0.0, 1|0.0, 2|0.0, 3|0.5, 4|1.0, 5|0.5, 6|0.0 ... 15|0.0]

Fair = [0|0.0 ... 4|0.0, 5|0.5, 6|1.0, 7|0.5, 8|0.0 ... 15|0.0]

Poor = [0|0.0 ... 6|0.0, 7|0.25, 8|0.5, 9|0.75, 10|1.0, 11|0.75, 12|0.5, 13|0.25, 14|0.0, 15|0.0]

Fail = [0|0.0 ... 10|0.0, 11|0.25, 12|0.5, 13|0.75, 14|1.0, 15|1.0]

Other functions would include fuzzy values for importance weights, hazard indices, overall intersection LOS, and any other variables that may be included.

4. Obtain an evaluation of an intersection from users or experts using the same linguistics describing LOS as mentioned above. For example, the delay category of 9 has the highest degree of membership in the Poor LOS category. A similar conclusion could be drawn using a predicted hazard index.
5. Determine the mean fuzzy value of the system and translate it to a natural language expression. Given that the operational level of service is poor, the safety level of service is fair, and operational LOS is of medium importance and safety LOS is of high importance, the fuzzy sets for these variables could be manipulated resulting in a fuzzy set representing the intersection's overall LOS. There exist three main methods for translating this function. The method most appropriate for situations in which the number of terms is small—as is the case for this problem—is the “best fit” method. Given a fuzzy set A , for example the one resulting from step 4, and a known fuzzy set B , in this case the overall LOS function determined in step 3, the Euclidean distance is calculated using the following formula:

$$D(A, B) = \left(\sum_{i=1}^N \{ \mu_A(i) - \mu_B(i) \}^2 \right)^{0.5}$$

where:

$D(A, B)$ is the Euclidean distance between fuzzy sets A and B ,

μ_A and μ_B are the membership values for elements i of A and i of B , and

N is the integer that defines the highest element in value in the two sets.

The application of the D function results in a combined LOS assessment for the intersection in natural language.

6. CONCLUSIONS AND RECOMMENDATIONS

This paper has presented the major issues involved in integrating safety into the *Highway Capacity Manual*, and has used a discussion of those issues to characterize the ideal method for assessing level of service at signalized intersections. Fuzzy sets are proposed as one tool that has the characteristics described. An example using of Fuzzy sets illustrates some of the main tasks required for implementation and, at a conceptual level, describes the various models used.

In summary, the paper supports the following conclusions:

- There exists a need for a safety-related level of service measure,
- No previous efforts have been made to integrate safety and operational levels of service wherein the issues as discussed were addressed,
- There exists a wealth of safety-related research that would facilitate the modeling of safety at signalized intersections,
- Given the weaknesses of current methods to assess service quality, and the special requirements for integrating safety, fuzzy sets hold great promise as an assessment tool within the HCM.

Future research should address the issues raised in this monograph, namely, the integration of safety into the HCM, the use of distinct, deterministic boundaries for LOS, and use of a sole LOS parameter.

It is hoped that this work is the first step toward providing accurate, safety based tools for assessing level of service of highway facilities. Clearly, many of the points made pertaining to signalized intersections, apply equally well to other types of facilities.

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